

AFFDL-T11-74-216-FBT

AIR FORCE FLIGHT DYNAMICS LABORATORY
DIRECTOR OF SCIENCE & TECHNOLOGY
AIR FORCE SYSTEMS COMMAND
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ADD420516

ACOUSTIC EMISSION FOR DAMAGE DETECTION
IN USAF COMPOSITE STRUCTURAL COMPONENTS

JANUARY 1975

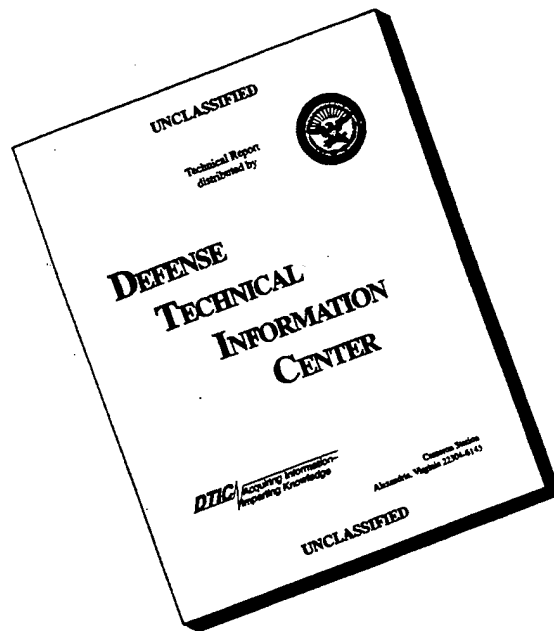
EXPERIMENTAL BRANCH
STRUCTURES DIVISION

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JANUARY 1975

R. A. NOBLE
EXPERIMENTAL BRANCH
STRUCTURES DIVISION

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FOREWORD

This report prepared and authored by Robert A. Noble, Project Engineer, Experimental Branch, Structures Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, covers work accomplished over the time period of April 1972 to April 1974. The in-house effort was initiated under Project No. 1347, "Structural Testing of Military Flight Vehicles", Task No. 134704, "Experimental Mechanics", Work Unit No. 13470405, "Acoustic Emission for Damage Detection in USAF Composite Structural Components".

Acknowledgement is given to Dr. Wolfgang A. Kapp, the initiator of this work unit, who served as Project Engineer until his death in July 1973, to Richard A. Kleismit and James L. Weiher for their invaluable assistance in the laboratory, to Viola Caslin for preparing the manuscript for publication, and to other employees of the Experimental Branch for their support.

This manuscript was released by the author in November 1974.

This Technical Memorandum has been reviewed and is approved.



ROBERT L. CAVANAGH
Chief, Experimental Branch
Structures Division
Air Force Flight Dynamics Laboratory

SECTION I
INTRODUCTION

1. [Filamentary composite materials, such as boron fibers in an epoxy matrix, are being used in modern USAF airframes.] Great weight and cost savings are expected when the reliability and maintainability of these composite airframes are proven in appropriate structural tests. The development of a measurement tool for laboratory tests of USAF composite airframe structures, sensitive to the accumulating damage in these complex airframes during test, is essential to such proof.

2. Acoustic emission monitoring techniques were developed and studied by a number of investigators who predicted the method should become a very useful tool with more definitive interpretation of results. [The objective of this project ^{is} ~~was~~ the development of a prototype acoustic emission system, including amplitude and frequency discrimination, which would provide definitive results and form the basis of a laboratory tool for monitoring tests of composite coupons and small components.]

(Authored, modified)

SECTION II

BACKGROUND

1. The late Dr. Wolfgang A. Kapp of this organization researched the acoustic emission literature and consulted with experts in the field. He decided that in addition to recording the acoustic emission counts and count rates, information as to their relative magnitudes and frequencies would help identify the source of the signals. The desire was to identify the failure mechanisms in composites, i.e. fiber breakage, fiber-matrix slippage, matrix deformation.

2. Toward that end he designed the system shown in Figure 1 which included a pickup unit, amplifiers, counters, a pulse height analyzer, a frequency spectrum analyzer, and recording equipment.

SECTION III

SYSTEM COMPONENTS

1. The pickup crystals selected were lead zirconate titanate (PZT) discs purchased from Valpey-Fisher Corporation. Two types were obtained, one with resonant frequency of 5 MC and the other with resonant frequency of 9 MC. The crystal was mounted on the end of a small plastic cylinder protruding from a shorter piece of tubing affixed to the side of a small box housing the first amplifier, or pre-amplifier. The plastic cylinder was free to move back and forth within the tubing as the crystal was deformed. Vacuum grease was used as a coupling medium between the crystal and the specimen.

2. The pre-amp was followed in the circuit by an impedance matching network and a general amplifier as shown in Figure 2. The impedance matching was required because the output impedance of the pre-amp was approximately 100 ohms and the input impedance of the general amplifier was on the order of 12000 ohms.

3. The frequency spectrum analyzer followed the general amplifier. It consisted of seven narrow band pass filters, each preceded by a buffer amplifier as shown in Figure 3. The seven filters were designed and assembled to operate with the following center frequencies: 100 kHz, 200 kHz, 400 kHz, 800 kHz, 1600 kHz, 3200 kHz, and 6400 kHz. The gain of each filter was then adjusted to approximately 40. The values of the components used in the individual filters are shown in Table 1, and the resulting relationship of output signal amplitude versus frequency of the input signal for each filter appears in Figure 4.

TABLE 1
FILTER COMPONENT VALUES (SEE FIGURE 3)

<u>KILO-HERTZ</u>	<u>KILO-OHMS</u>				<u>PICO-FARADS</u>			<u>KILO-HERTZ</u>
<u>FILTER</u>	<u>R₁</u>	<u>R₂</u>	<u>R₃</u>	<u>R₄</u>	<u>C₁</u>	<u>C₂</u>	<u>C₃</u>	<u>f_c</u>
100	17.5	2	0.	.200	1500	3000	0.	105
200	77.5	2	0.	.200	750	1500	0.	206
400	3.7	2	0.	.200	390	150	0.	371
800	7.5	2	6.9	.240	150	330	150	830
1600	36.0	2	0.	.220	68	150	50	1632
#3200	1.2	2	22.	.240	24	50	100	3301
*#6400	.820	2	0.	.200	10	20	0	6494

* The two 1K resistors were replaced with 560 ohm resistors on the 6400 kHz filter.

A 10 pf capacitor was added in parallel to one of the 68 pf capacitors on the 3200 and the 6400 kHz filters for increased stability.

4. The pulse height analyzer was an E.L. Instruments, Inc., Model 501, Five Channel Analyzer. It consisted of a preamp feeding five single channel analyzers in parallel. An amplitude window could be set for each channel thus determining the range of pulse heights to be detected. Each channel delivered an output pulse for each input pulse whose amplitude fell within its preset window, and an analog output proportional to the rate at which pulses fell within the window.

5. Counters used to indicate the number of output pulses detected were Eldorado Electrodata Corporation, Model 1607 Counter/Timers.

6. The output of the frequency spectrum analyzer was recorded on a 14-channel Bell and Howell VR-3700B Magnetic Tape Recorder.

7. The tape was then played back and selected outputs recorded on a 6-channel Brush Model 360 recorder.

SECTION IV

RESULTS

1. Assembly of the acoustic emission system, as designed for evaluation as a detector of structural damage in composites, has been completed. It consists partly of commercially available equipment and partly of in-house construction.

2. A sample of the output of this system appears in Figure 5. The pickup sensor was placed in contact with a block of wood, about 8" x 2" x 4". A small teflon ball was dropped on the wood. The resulting stress waves were recorded at a tape speed of 60 inches per second. The tape was played back at 1-7/8 inches per second and recorded on the Brush recorder at a chart speed of 125mm/sec. The system was then ready to enter the next phase of the effort, that of recording acoustic emissions from stressed specimens for the purpose of trying to identify signatures of failure mechanisms in composites.

3. The opportunity existed to obtain such data during a series of on-going tests. Therefore, the transducer was mounted in contact with three titanium and three boron composite specimens, in turn, as they were loaded to failure. In addition, two boron composite specimens obtained specifically for this project were monitored as they were failed in tension. Examination of the data revealed that the desired information was lacking presumably due to operational and/or design deficiencies.

4. To confirm that opinion and to help determine the future course of the project, an internationally recognized expert in stress waves and acoustic emission was hired as a

consultant. The resulting report of Dr. Yosio Nakamura, Associate Professor, The University of Texas, Marine Science Institute Geophysics Laboratory, Galveston, Texas, appears as Appendix I. In essence, he commended the intent and plan of the project and recommended substitution and/or addition of specified component parts to effect improved system performance.

5. Further effort in this technical area has been indefinitely postponed due to higher priority projects. Related efforts will include monitoring of large-scale metallic structures in the structures test laboratory by means of conventional acoustic emission equipment.

ON LINE FREQUENCY SPECTROMETER (REAL TIME)
(PSD - ANALYZER) UP TO 23 CHANNELS
100 KHZ - 6 MHZ

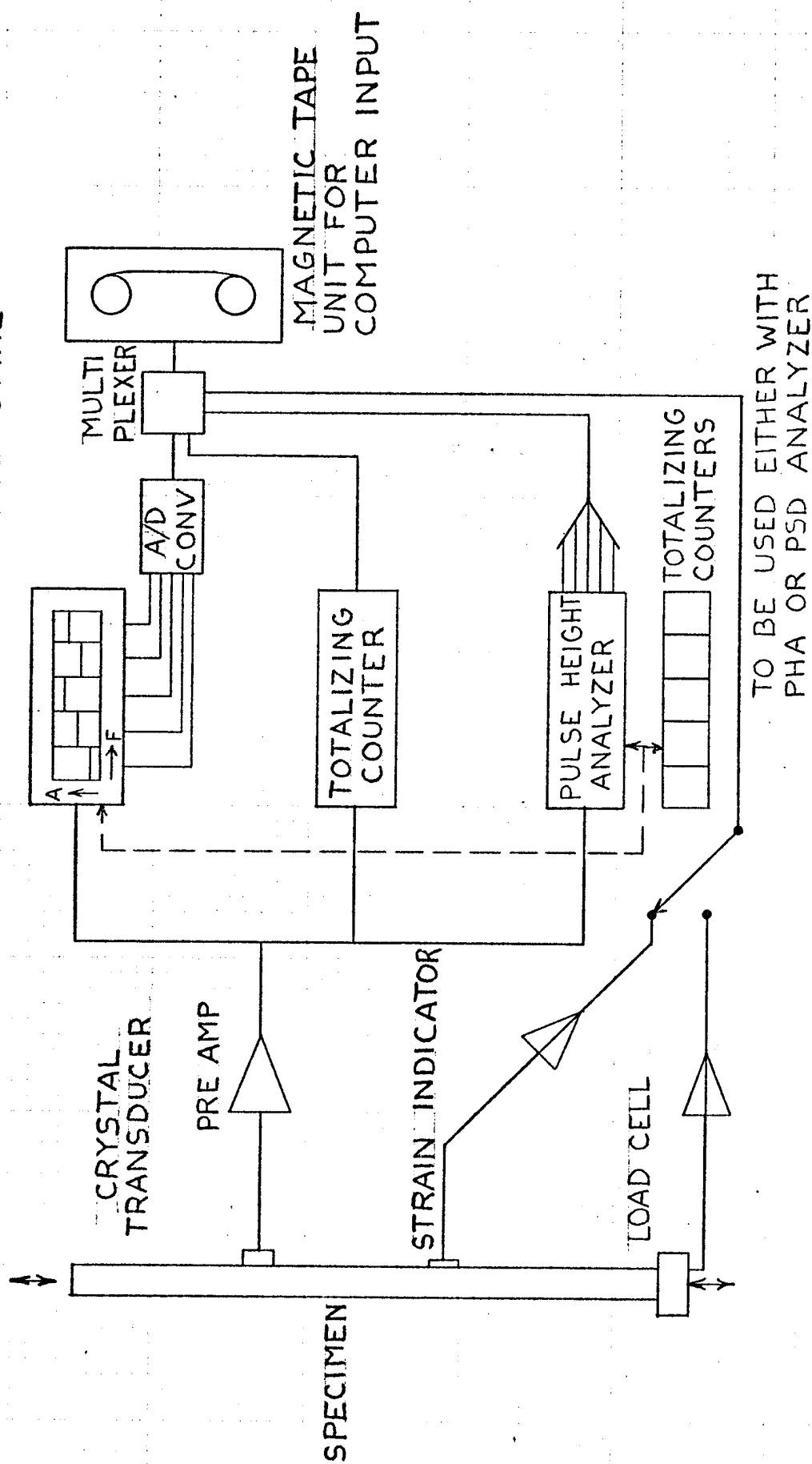
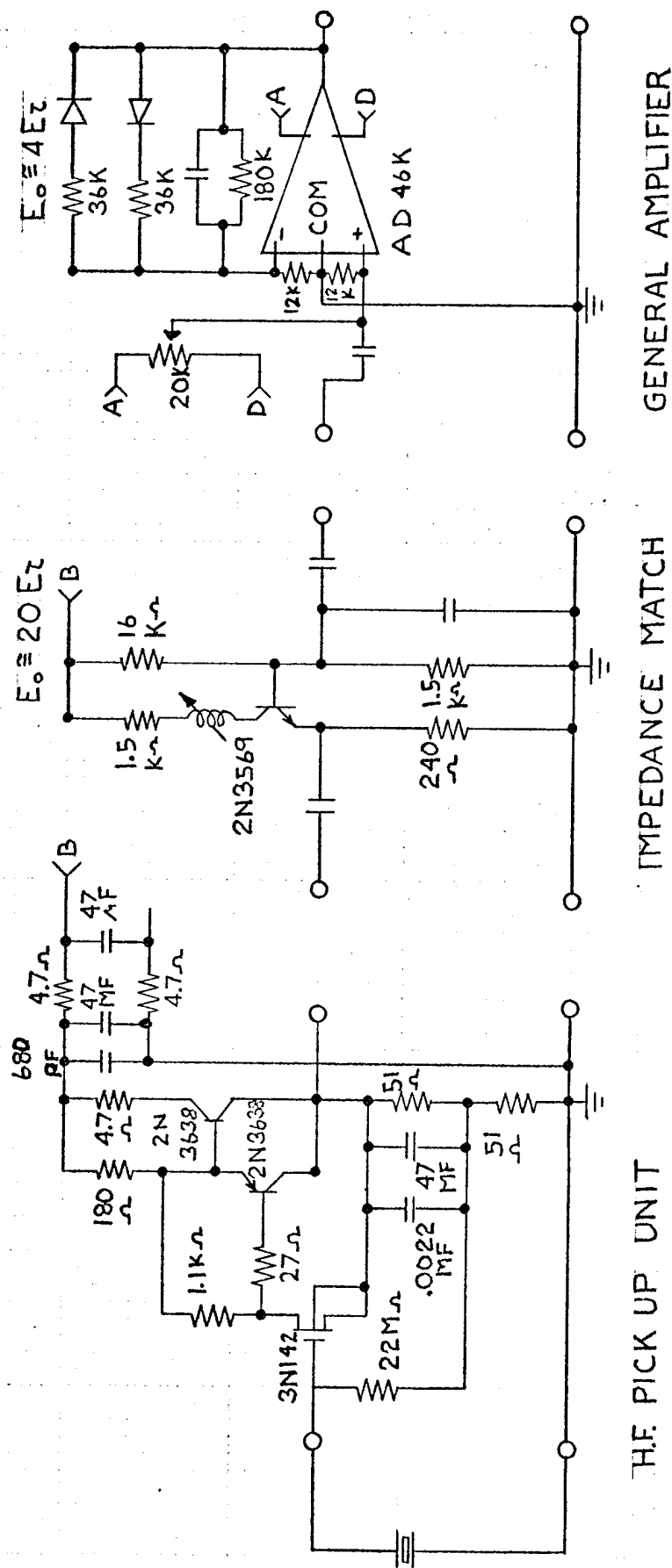


FIG. 1. ACOUSTIC EMISSION MONITORING SYSTEM



- A +15 VDC
- B +10 VDC
- C +5 VDC
- D -15 VDC

FIG. 2. AMPLIFIERS

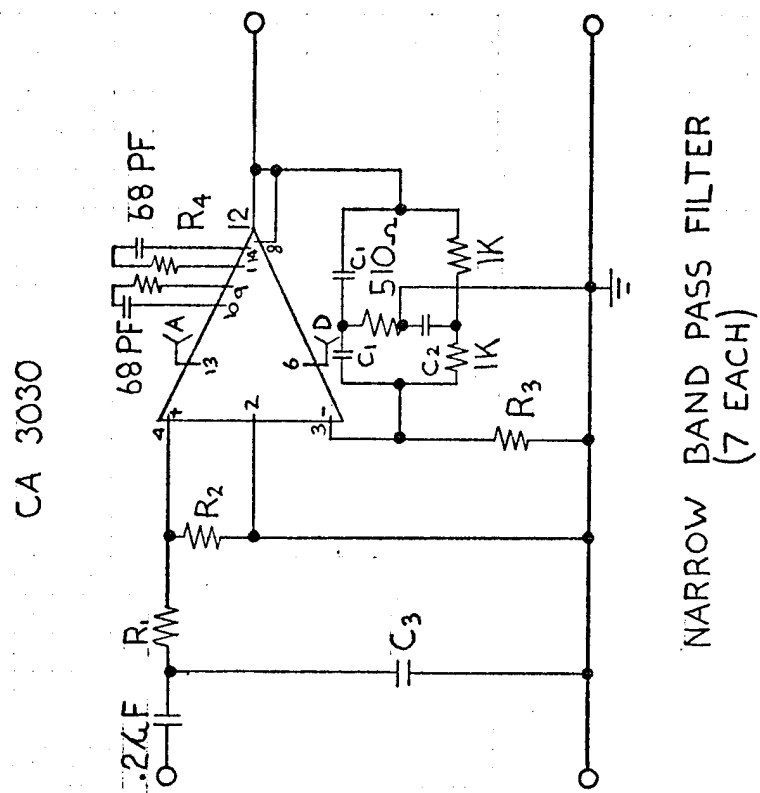
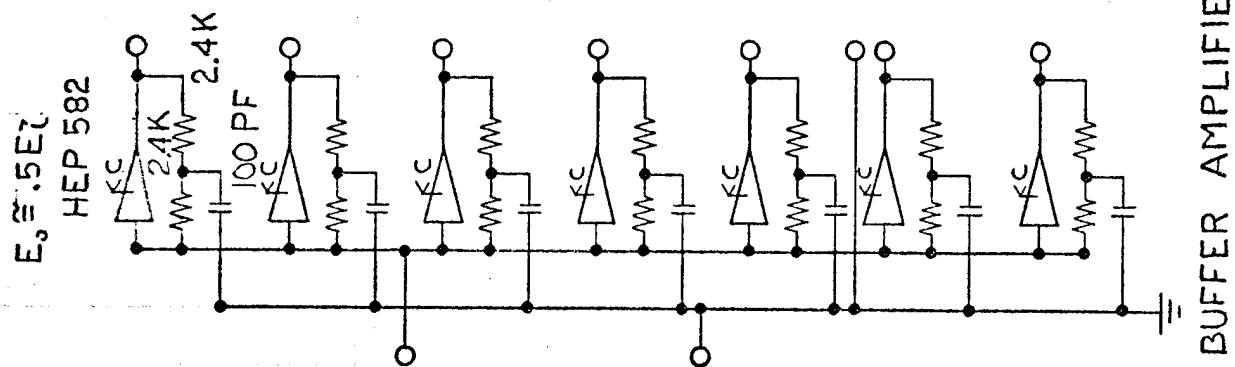


FIG.3 FREQUENCY SPECTRUM ANALYZER

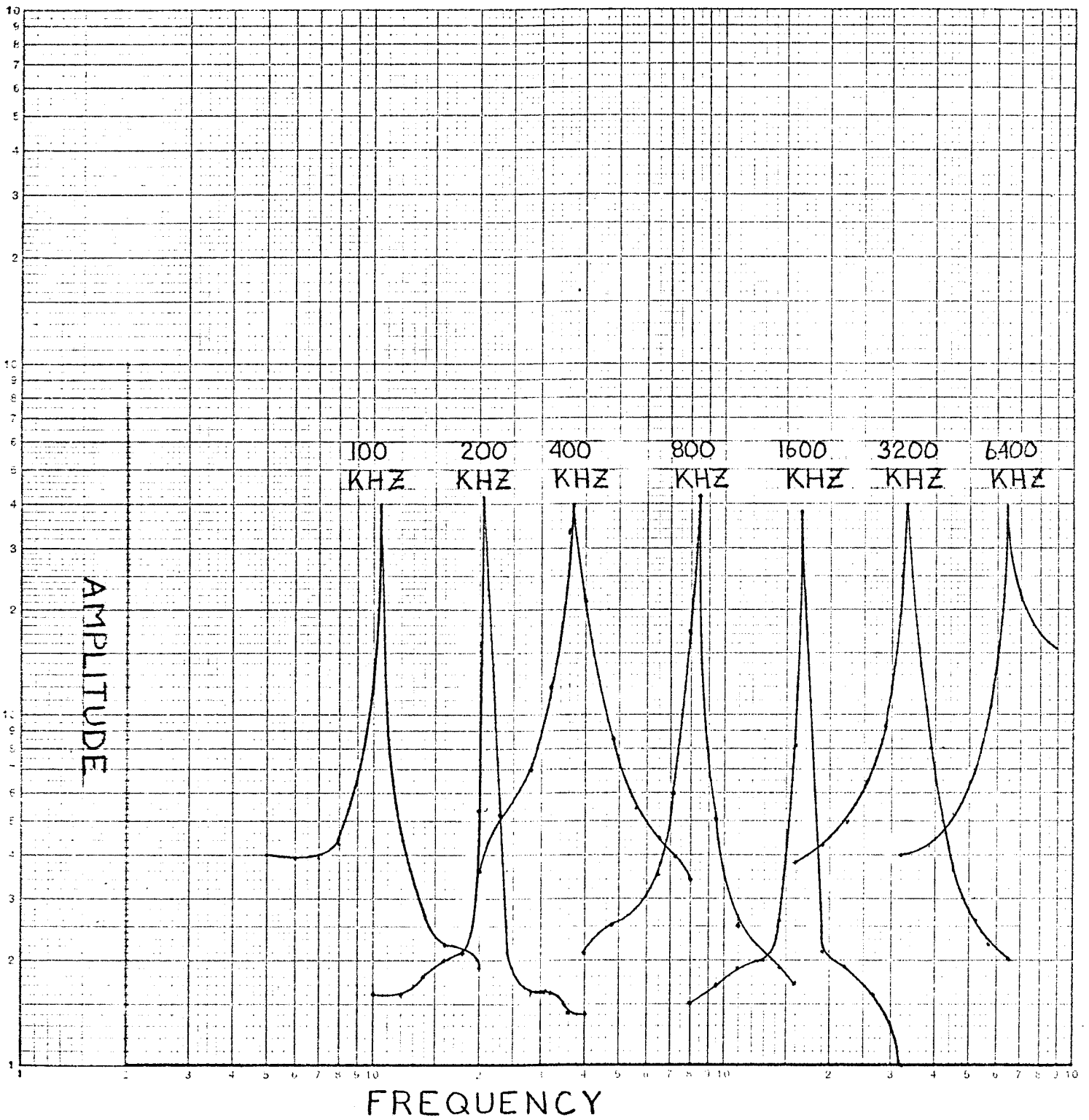


FIG. 4. FILTER OUTPUTS

UNFILTERED
SIGNAL

50mv/mm

CHART SPEED 125mm/sec
TIME

100 KHZ FILTER

10mv/mm

TAPE RECORDED AT 60 I.P.S.
TAPE REPLAYED AT $1\frac{7}{8}$ I.P.S.

200 KHZ FILTER

10mv/mm

400 KHZ FILTER

10mv/mm

FIG. 5. SAMPLE DATA OUTPUT

800 KHZ FILTER

10mv/mm

APPENDIX I
An Information Letter Report
on
Appraisal of AFFDL Acoustic Emission Spectral/Amplitude
Analysis Project, including Evaluation of and Recommendations
on AFFDL Spectral/Amplitude Analyzer System

Submitted to: AFFDL (FY 1456)
ATTN: AFFDL/AC
Contract No. F33615-72-C-2193
Item No. 0002, Sequence No. AFFDL/AC Request No. 52
Wright-Patterson Air Force Base, Ohio 45433

Prepared by: Yosio Nakamura
Marine Science Institute
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Galveston, Texas 77550

Date: September 30, 1974

I. Introduction

The acoustics emission spectral/amplitude analysis project of the U.S. Air Force Flight Dynamics Laboratory was reviewed and examined on 24, 25 and 26 September 1974. This report describes the findings of the review and gives recommendations as to the future course of the project. A special emphasis is placed on evaluation of and recommendations on the spectral/amplitude analyzer system to be used for the pursuance of the project.

II. Evaluation of Overall Approach

The basic approach of this project, where acquisition and analysis of combined data of spectral content and amplitude distribution of acoustic emission(AE) signals from composite materials are being attempted, has been evaluated in view of the AFFDL's approach to the entire AE project as well as of the state of the art of AE research and applications. The AFFDL's overall AE effort has dual purposes: one is to use AE as an NDI tool for achieving flaw detection in air frames at improved reliability and reduced cost, and the other is to use AE as a laboratory research tool to obtain better understanding of fracture mechanisms in materials used for aircraft structures. This balanced approach is highly commended, and the present project has a great value in this overall AE effort.

The approach of the project is judged sound, because it attempts to open up new dimensions to characterization of AE signals. Many people have tried in the past to characterize AE signals simply by counting emission signals with limited success. Frequency spectrum and amplitude distribution of AE signals are two of the areas where very little work has been done in the past, and exploration into these two areas

is greatly needed today. When applied to tests of composite materials, this new approach has high potential of supplying extremely valuable information on fracture process of such materials, provided that right personnel to conduct this project are available.

III. Evaluation of Analyzer System

The system setup as originally designed by Dr. Kapp was probably appropriate for the specific purpose of his experiment at the time he conceived this experiment. However, the setup is not for general use and other people will find it difficult to use the setup at its present form. Furthermore, AE equipment now available on the market are much more advanced from those which were available two years ago, although no commercially available AE system at present is yet capable of satisfying the requirement of this project. Therefore, to make the system more suitable for general use, it would be best to evaluate each component of the present system and to replace those components to which better substitutes are commercially available.

System Component Evaluation

1. Transducer: The use of bare transducers, as in the present system, is preferable to commercially available AE transducers in an experiment of this type because of the simplicity of specimen/transducer interactions.
2. Preamplifier: The present, home-made preamplifier was found to be inferior to most commercially available preamplifiers. Preamplifiers of much better quality, in terms of noise level, gain and dynamic range, are available at reasonable cost.
3. Main Amplifier: The same comment as above applies to this component.

4. Frequency Analyzer Unit: There are several alternative methods to obtain similar information, but the simplicity of the present method is well worth consideration. Unfortunately, a test revealed several difficulties and malfunctions, some of which seem to be due to design problems. Specifically, (1) the buffer amplifier in each section does not have sufficient gain and stability at frequency of interest, (2) some of the narrow-band filters are unstable and side lobes are not well behaved, and (3) the present output signals from the unit are not convenient for data presentation.

5. Amplitude Analyzer: The way the present unit processes signals for amplitude is not quite appropriate for obtaining meaningful information. Two major difficulties are (1) amplitude discrimination without necessary pre-processing of signals and (2) narrow dynamic range (less than 20 dB). There will be an amplitude distribution analyzer unit suitable for AE signals available in market in the near future, and a replacement with this unit would probably be the best approach.

6. Presentation of Output: This area has not yet been developed in the present system. The use of a magnetic tape record and a multi-channel strip-chart recorder is proper, and the ones in the present system are appropriate for convenient data handling. The interface between the analyzers and these output devices, however, needs further development.

Other Features

1. The present system analyzes signals from a single transducer. Consequently, there will be no information available as to the source locations of detected signals. An addition of supplementary channel for signal recording will be a useful addition.

2. The system has no provision for taking conventional emission-count data. The data will be useful when comparison with results of other investigators is desired.

3. Data recorded on a magnetic tape without time code are difficult to retrieve. An addition of time-code generator/reader and a tape search unit will greatly increase the data playback capability.

4. For a research that requires observation of waveforms, a good variable-frequency filter is an almost indispensable tool.

IV. Recommendations

The following is a set of recommendations based on the above evaluation of the project and available equipment.

Recommendation 1. The project should be continued as planned.

Recommendation 2. The equipment setup should be reconstructed by replacing defective components, redesigning and rebuilding the frequency analyzer unit, and adding some necessary components. A recommended setup at this time is the one that uses the basic principle of the present setup with certain necessary revisions. One example of such a setup is shown in Figure 1. Anything more sophisticated than such a setup, for example, computer analysis of digitized waveforms, is not recommended at this time. Such a setup should be designed by the project leader under his full control.

Specific recommendations for components of the setup in Figure 1 are as follows:

1. Transducers (2) - Bare transducers as in the present setup. Smaller ones may be required.

2. Preamplifiers (2) - Use commercial ones. Important specifications are low noise, wide band and wide dynamic range (60 dB). A gain of 40 dB probably is most useful.
3. Amplifiers (2) - Use commercial, wide-band amplifiers of adjustable, calibrated gain.
4. Frequency Analyzer - This unit is not commercially available. Therefore, re-examine the present design and rebuild the unit. The following points need particular attention:
 - (1) Buffer amplifiers - redesign to obtain sufficient gain and stability at respective frequencies.
 - (2) Narrow-band filters - re-examine to achieve improved stability and well behaved side lobes.
 - (3) Output circuits - design a circuit to produce output suitable for the tape recorder and the Brush recorder. Such circuit as that which produces a square pulse of a height proportional to the peak amplitude of the input signal and of a duration long enough for the recorder responses may be suitable.
 - (4) Overall construction - a modular construction compatible with other components of the system is most convenient.
5. Modified EL Analyzer - With minor modifications, this unit can be used as a discriminator to obtain conventional emission counts. Voltage output proportional to the count rate is available at the 'A' output

terminal, and the 'D' output pulses can be counted on one or more Eldorado counters in rate and/or cumulative mode.

6. Time-Code Generator/Reader - IRIG A (10 kHz carrier) is more convenient than IRIG B (1 kHz). Slow-code option is very useful.
7. Tape Search Unit - Milli-second resolution is needed.
8. Variable Frequency Filters (2) - Those which cover up to 3 MHz in band-pass mode are suitable for this setup.
9. Amplitude Distribution Analyzer (optional) - This unit will be commercially available in the near future. It replaces the EL analyzer in the present system.
10. Spatial Discrimination Unit (optional) - This commercial unit has three types of spatial discrimination capabilities including coincidence detection of signals.

A typical set of data to be recorded on a magnetic tape and that on a strip chart are listed in Tables 1 and 2, respectively.

A total estimated cost of purchasing additional commercial equipment, not including the optional equipment, will be between \$3,000 and \$10,000, subject to in-house availability of some components.

Recommendation 3. Utilization of right personnel is of utmost importance in a project of this type. A good electronic technician is needed both during the development of the measurement system and during the use of the system for proper care of equipment. For correct interpretation of AE results, involvement by personnel familiar with fracture mechanics will be a great asset.

TABLE 1

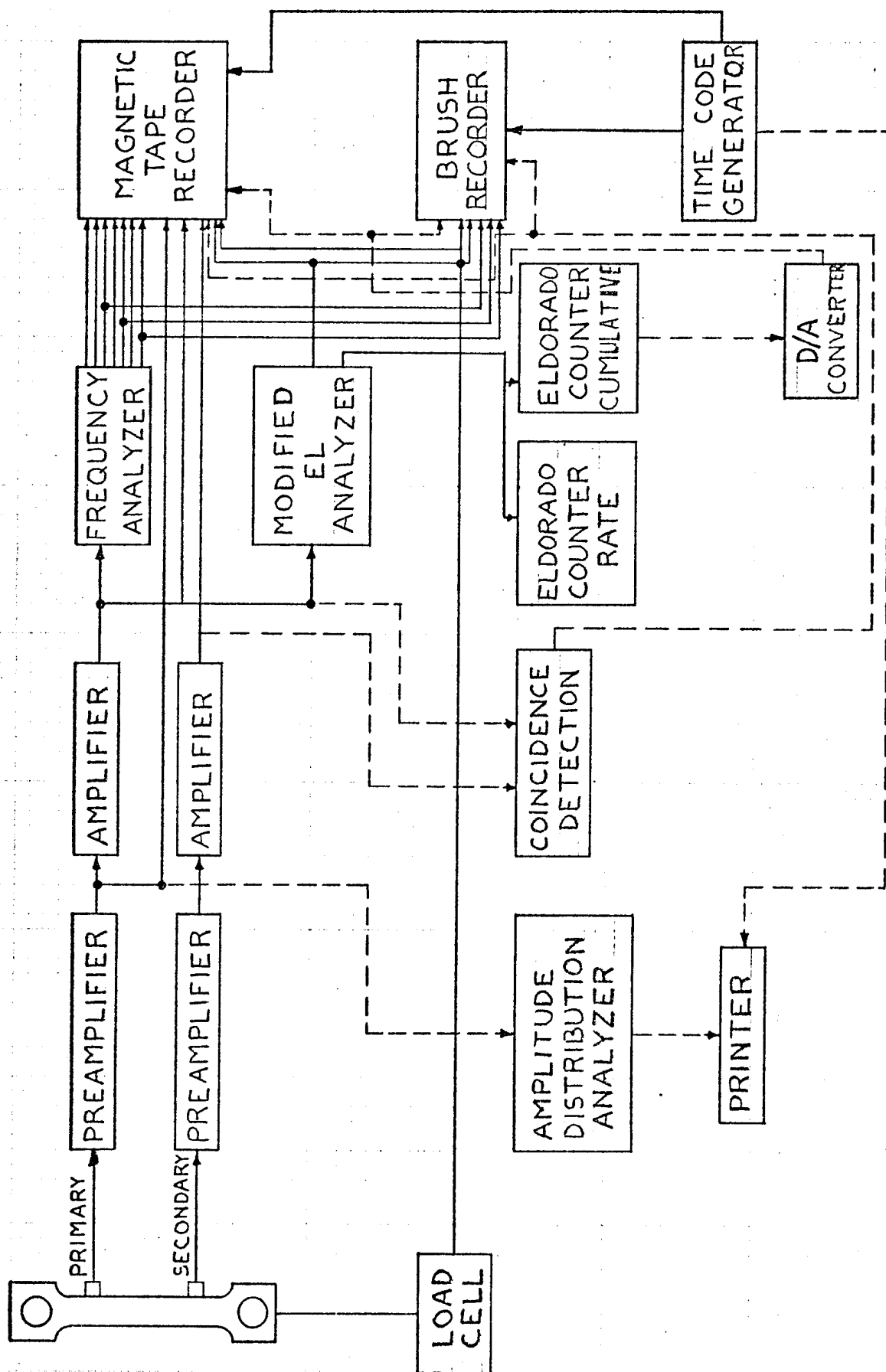
A TYPICAL SET OF DATA TO BE RECORDED ON MAGNETIC TAPE

	<u>DATA</u>	<u>MODE</u>	<u>REMARKS</u>
1.	Primary analog signal, high level	Direct	300 μ V - 10 mV
2.	Primary analog signal, low level	Direct	10 μ V - 300 μ V
3.	Secondary analog signal, low level	Direct	10 μ V - 300 μ V
4.	Frequency analyzer output 1	FM	
5.	Frequency analyzer output 2	FM	
6.	Frequency analyzer output 3	FM	
7.	Frequency analyzer output 4	FM	
8.	Frequency analyzer output 5	FM	
9.	Frequency analyzer output 6	FM	
10.	Frequency analyzer output 7	FM	
11.	Time Code, IRIG A	FM	
12.	Load Level	FM	
13.	Count rate analog	FM	from EL analyzer
14.	Cumulative count analog	FM	Optional

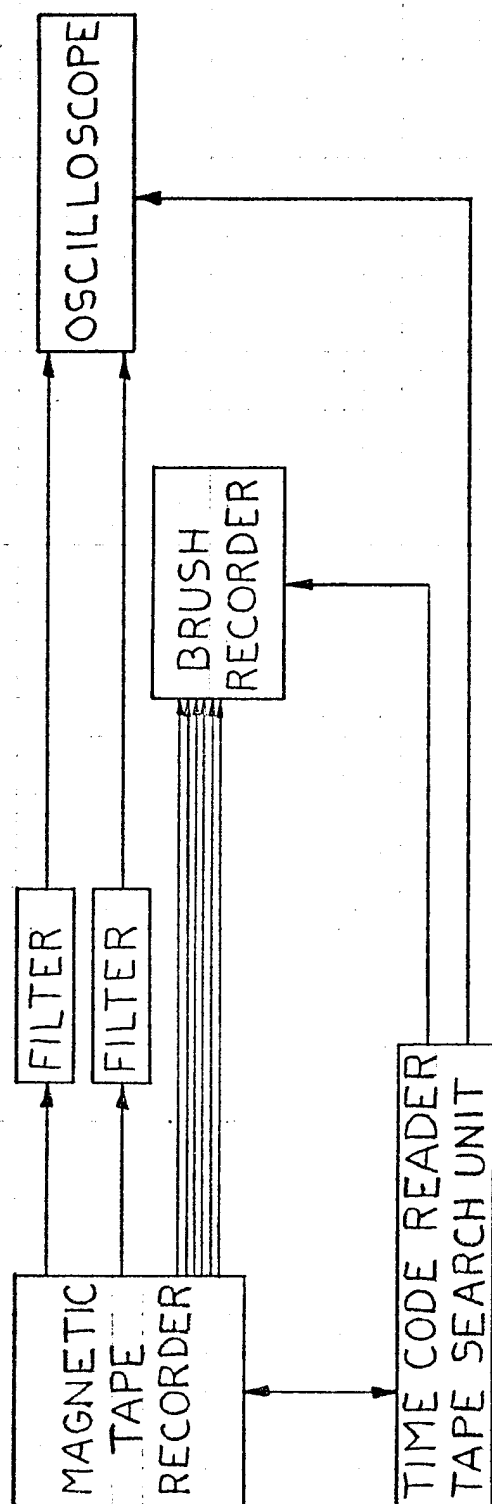
TABLE 2

A TYPICAL SET OF DATA TO BE RECORDED ON A BRUSH RECORDER CHART IN
REAL TIME OR FOR PLAY BACK

1. Frequency analyzer output
2. Frequency analyzer output
3. Frequency analyzer output
4. Load Level
5. Count Rate
6. Cumulative count (Optional)
7. Time Code (slow code) on event marker



APPENDIX I, FIG 1A SETUP FOR DATA ACQUISITION



APPENDIX I, FIG 1B, SETUP FOR DATA PLAYBACK